PCT Patent Application

Series Fans with Flow Modification Element

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Priority

This application claims priority from US 60/520,678 (High performance Series Fan Configurations, filed November 18, 2003) and US 60/520,676 (Dual Redundant Cooling Fan Sinks and Trays, filed November 18, 2003)

Field of the Invention

This invention relates to a unique series fan configuration intended for cooling electronics. The configuration is modular, extremely compact, fault tolerant, and uses readily available low cost axial fans. A display panel may be configured to alert the user regarding a failed fan, which may then be replaced (or "hot swapped") without shutting down the system being cooled.

Acknowledgement of Prior Art

The need for highly reliable, fault tolerant, and hot swappable cooling fans has increased as the mission critical use of high performance electronics becomes more and more prevalent. In many cases a loss of cooling for more than a brief moment could damage the underlying electronic components.

This has driven a tremendous amount of inventive activity in the field as evidenced by numerous recent patents including US patent 6,247,898 issued June 19, 2001 to Henderson, et al (assigned to Micron Electronics), US Patent 6,108,203 issued Aug. 22, 2000 to Dittus, et al (assigned to IBM), US patent 6,101,459 issued Aug. 8, 2000 to Tavallaei, et al (assigned to Compaq Computer), US patent 6,061,237 issued May 9,

2000 to Sands, et al (assigned to Dell Computer), US patent 6,040,987 issued Mar. 21, 2000 to Schmitt, et al (assigned to Dell), US patent 6,031,717 issued Feb. 29, 2000 to Baddour, et al (assigned to Dell Computer), US patent 6,021,042 issued Feb. 1. 2000 to Anderson, et al (assigned to Intel Corporation), US patent 6,005,770 issued Dec. 21, 1999 to Schmitt (assigned to Dell Computer), US patent 5,572,403 issued Nov. 5, 1996 to Mills, et al (assigned to Dell Computer), and US patent 5,562,410 issued Oct. 8, 1996 to Sachs, et al (assigned to EMC Corporation),

Most of these patents, including US Patent 6,108,203 assigned to IBM, US patent 6,101,459 assigned to Compaq, US patent 6,061,237 assigned to Dell, US patent 6,031,717 assigned to Dell, US 6,021,042 assigned to Intel, and US patent 6,005,770 assigned to Dell teach redundant fans operating in parallel. Of these, US 6,108,203, US 6,061, 237, US 6,031,717, US 6,021,042, and US 6,005,770 all teach various types of baffling to prevent the reverse flow of air through the defective fan, and the ensuing loss of cooling air pressure within the cabinet. US 6,101,459 teaches that this reverse flow of air may be prevented by placing a second, back-up, fan in series with each of the parallel fans. However it must be noted that this same patent also teaches that the back-up fans remain idle until required. These patents also suggest various ways to ease the process of replacing the defective fan(s). US 6,061, 237 teaches that two parallel fans may be placed at an angle to save space.

Only two of these patents, US 6,101,459 assigned to Compaq and US 5,572,403 assigned to Dell, suggest a series configuration for the cooling fans. Of these, US 6,101,459 teaches that the second fan in the series is for back-up purposes only, and will remain idle until required as previously noted. US 5,572, 403 does teach that the series configured fans run simultaneously, in counter-rotating fashion, and further teaches that a plenum bypass be used to reduce impedance and increase airflow in the event of a fan failure. However this approach requires specialized fans and also requires further baffling within the cabinet to accommodate the plenum bypass flow when required.

An additional two of these patents, US 6,040,981 assigned to Dell and US 5,562,410 assigned to EMC address the issues of easy fan removal and hot swappable fans. US 6,040,981 teaches a removable fan with camming handle that aligns the fan and re-

connects power in a single operation. US 5,562,410 teaches a self aligning hot-pluggable fan assembly, primarily to complement the fault tolerant characteristic of RAID based disk arrays.

Finally, US 6,247,898 teaches a method of controlling the speed of a plurality of fans connected in parallel fashion.

Summary of the invention

As taught by prior art, a currently accepted solution is to install dual fans (or blowers) in a parallel configuration such that one fan has the capacity to cool the entire cabinet, at least on a minimal cooling basis. In this manner, the failure of one fan can be tolerated without damaging the equipment. While this approach works, the parallel installation has the following associated problems; (1) mounting two fans side by side requires twice as much cabinet wall space, and increases the potential for Electro-Magnetic (EM) leakage through the fan opening, (2) the fail over mechanism must contain sufficient baffling to prevent air from escaping (or entering) through the defective fan, a complex and bulky approach, (3) further baffling is required to ensure that the air stream is directed consistently regardless of which fan is operating, and (4) the system may need to be shut down before replacing the defective fan.

There are benefits to mounting the fans in series rather than in parallel – i.e. place one fan behind the other rather than one fan beside the other. However the problem with this approach has been that two fans in series do not perform well because the airflow produced by the primary fan contains swirl, and this does not match the ideal input conditions for the secondary fan. The secondary fan must have a substantially reduced level of swirl at its input to operate efficiently.

Despite this drawback, the series configuration solves many of the problems associated with the parallel configuration; (1) a series configuration takes less cabinet wall space than a parallel configuration, and therefore reduces the potential EM leakage, (2) no baffling is required to prevent air from escaping through the defective fan – in fact air must flow through the defective fan in order for the series configuration to work, (3) no

further baffling is required to ensure that the air is consistently directed since the two fans are mounted on the same or similar axis, and (4) a defective fan may be safely replaced or "hot swapped" without shutting down the system or components being cooled.

Accordingly the present invention discloses a method of reducing the swirl between the two fans by placing a flow modification element, or diffuser element, between the two fans, so that the above benefits can be realized. The present invention also discloses several additional features that will contribute to functionality, ease of use, ease of maintenance, and lower cost such as; (1) an integrated filter / flow control element, (2) a user interface panel to show the status of both fans and the integrated filter element, (3) the ability to replace the filter element or the defective fan from outside the cabinet while the system is running, and (4) a very compact and modular device that can be installed between two industry standard fans to create a high performance series fan configuration. Further, the present invention discloses many applications for high performance series fans such as for the cooling of components, heat sinks, system cabinets, and enclosures.

It is commonly known that an axial fan works best if it sees laminar flow on the input side. This condition is met with a single fan since there is nothing on the input side to generate swirl. However this is not the case with a series configuration since the output of the primary fan, as in the case of all axial fans, contains swirl.

The present invention discloses that this problem may be resolved by placing a diffuser element between the two fans. The result of placing a diffuser element between the two fans is to substantially reduce the swirl produced by the primary fan before the airflow enters the secondary fan, thereby increasing the efficiency of the secondary fan.

The use of an intermediate diffuser element will not affect the primary inherent advantages of a series fan configuration - the airflow will always be in the same direction, even during a fan failure, and no baffling changes will be required within the cabinet to re-direct the flow during a fan failure. In the event of a primary (or input) fan failure, the secondary (or output) fan will continue to "pull" air through the diffuser element and move it in the same direction. Likewise air will continue to flow in the same

direction if the secondary fan fails, except that the primary fan will "push" rather than "pull" air through the diffuser element.

Although the *direction* of airflow will remain consistent in a series fan configuration with a single fan failure, the *volume* of airflow will be reduced if the remaining fan continues to operate at the same speed. This is an acceptable situation only if the volume of airflow does not fall below the minimum required to dissipate the heat generated by the components being cooled. The present invention teaches that a control system may be configured to sense the fan failure and adjust the remaining fan speed accordingly, in order to ensure that this minimum requirement is met until the defective fan can be replaced. This type of control may be easily implemented since (1) many fans today are available with fault sensors to indicate an impending failure / total failure and (2) fan speed can be easily controlled by controlling the input parameters such as voltage, in the case of DC fans, or through pulse width modulation.

The efficiency of the series fan configuration, while in single fan failure mode, may be increased by allowing the diffuser element to swing or slide out of the air flow, for example by splitting the diffuser element down the middle and allowing each half to swing out of the flow, or otherwise partially or completely removing the diffuser element from the air flow until the defective fan may be replaced. Further, the efficiency of the series fan configuration, while in a single fan failure mode, may be increased by partially or completely removing the failed fan from the configuration until such time as it may be replaced. Further, the efficiency of the series fan configuration, while in a single fan failure mode, may be increased by providing a diffuser element bypass channel configured to allow the free flow of air past the diffuser element while in failure mode.

Should a fan fail, the present invention teaches that it may be replaced without having to shut down the system or components being cooled. High performance series fans may be configured as a "sliding drawer" that can be pulled away from the cabinet without interrupting the airflow. The defective fan may be replaced while the drawer is in the "open" position, and then the drawer may be returned to the "closed" position without affecting system operation or necessitating a system shut down. The control system will detect the new fan, and adjust speeds accordingly.

In some cases it may be possible to enhance the functionality of the diffuser element by configuring it as a combined filter / diffuser element, to reduce swirl and prevent particles from entering the system being cooled, a combined heat exchanger / diffuser element, to reduce swirl while adding or removing heat from the airflow, a combined Electro-Magnetic (EM) shield / diffuser element, to reduce swirl while maintaining the integrity of the EM shield in the fan opening, or other possible combinations. In larger applications the diffuser element may be active rather than passive so that the flow control parameters may be adjusted and optimized while the high performance series fan configuration is operating.

Various configurations are possible including a tightly coupled or modular arrangement, or a loosely coupled or push / pull arrangement. In a tightly coupled arrangement a primary fan and a secondary fan may be mounted at opposite ends of an air channel, in a substantially coaxial configuration, such that the air channel contains the diffuser element, and directs the airflow from the output of the primary fan, through the diffuser element, and into the secondary fan. In a loosely coupled or push / pull arrangement a primary fan blows air into an enclosed space and a secondary fan blows air out of the same enclosed space, and the components within the enclosed space act as a type of diffuser element to remove swirl from the airflow as it moves from the primary to the secondary fan. In some loosely coupled configurations a diffuser element may also be installed on the input side of the secondary fan to further reduce the swirl and improve the efficiency of the secondary fan, and baffling may be added to improve the efficiency of the airflow within the enclosed space.

The performance of the secondary fan may be enhanced by increasing the residual momentum and reducing the swirl component of the airflow at its input, as previously described. The primary fan contributes to this enhanced performance, since it increases the residual momentum of the airflow entering the secondary fan, however it also introduces a swirl component that is counter-productive. An optimized high performance series fan configuration retains a maximum level of residual momentum while reducing swirl to an ideal level before the airflow enters the secondary fan.

The total output of a series fan configuration, relative to the theoretical output of a non-optimized series fan configuration (generally considered to generate two times the static pressure for any given CFM output), may be expressed, in simple terms, as follows;

(1) $Output_T = (2 \times Output_S) + M - S$

Where $Output_T$ = Total output
$Output_S$ = Output from single fan
M = Momentum Factor (at secondary fan)
S = Swirl Factor (at secondary fan)

The momentum factor will naturally decay as the distance between the primary and secondary fans is increased, and as more restrictions, e.g. a diffuser element, are placed in the airflow. From this perspective the most effective series fan configurations will have the *least* possible distance between the primary and secondary fans, the *closest* co-axial alignment between the two fans, and the *least* number of restrictions between the two fans.

The swirl component will also naturally decay as the distance between the primary and secondary fans is increased, and from this perspective the most effective series fan configurations will have the *greatest* possible distance between the primary and secondary fans. The present invention teaches that this distance may be substantially reduced by installing a diffuser element between the primary and secondary fans to force a more rapid decay of swirl, as previously described. In a loosely coupled series fan configuration the components to be cooled may serve as a type of diffuser element, as in the case of a computer system where the primary and secondary fans are located at opposite ends of the cabinet and the air flowing between them must pass over the electronic components. Alternatively the diffuser element may be a purpose built component placed strategically between the two fans, or in front of the secondary fan. In either case the flow straightening element(s) will have both a positive and a negative effect since will it reduce the swirl component while at the same time increasing drag.

Based on this information the model may be re-constructed as follows;

(2) $Output_T = (2 \times Output_S) + M - S + (S_R - D)$

Where S_R = Swirl reduction factor
D = Drag introduced by swirl reducing components

Equation (2) may be re-written as follows to separate the behaviour of the primary and secondary fans, and associate this behaviour with the most closely aligned correction factor, as observed;

(3) $Output_T = (Output_{SP} - D) + (Output_{SS} + M - (S - S_R))$

Where $Output_{SP}$ = Output of a single primary fan
$Output_{SS}$ = Output of a single secondary fan

It is important to note that $Output_{SP}$ and $Output_{SS}$ both represent the output of single fans operating in independent fashion. It follows that $Output_{SP}$ and $Output_{SS}$ will be the same for a symmetrical series fan configuration, where the primary and secondary fans have identical specifications, and that $Output_{SP}$ and $Output_{SS}$ will be different for an asymmetrical series fan configuration, where the primary and secondary fans may have different specifications.

Clearly, then, the optimization objectives are to simultaneously maximize the momentum of airflow as it enters the secondary fan (M), minimize the swirl component of the airflow as it enters the secondary fan ($S - S_R$), and minimize the drag introduced by the swirl reducing components (D). In fact the output of the secondary fan may be enhanced, in this manner, to the extent that it exceeds $Output_{SS}$, i.e. it exceeds the output of a single secondary fan operating in independent fashion with input conditions that meet design specifications. It follows that the total output of a high performance series fan configuration with a diffuser element may exceed the theoretical output of two single fans as long as the following optimum condition exists;

(4) $M > ((S - S_R) - D)$

It has been found that an optimal condition may achieved by (1) mounting the primary and secondary fans coaxially at either end of a sealed air conducting tube or connecting sleeve, adapted with internal features such as longitudinal grooves or octagonal corners to induce natural swirl decay while maintaining the maximum level of momentum as the air flows between the two fans, and (2) by placing the diffuser element at a distance from the primary fan such that a substantial amount of natural swirl decay will have occurred before the airflow enters the diffuser element, as depicted in Figure 24 (with reference to the following components and corresponding numbers for Figure 24 only);

Component	*No.*	*Component*	*No.*
Primary Fan	200	Secondary Fan	202
Diffuser Element	204	Seal	206
Airflow	208	Integrated Stator	210
Acoustic Gap	212		

The diffuser element may be further optimized to remove substantially all of the remaining swirl while introducing a minimal level of incremental drag, thereby "straightening" the airflow while maintaining its momentum at the highest possible level as it leaves the diffuser element, and converting swirl energy to kinetic energy with the highest possible efficiency. The diffuser element may be placed immediately before or in close proximity to the secondary fan in order to maintain this momentum as the airflow enters the secondary fan, recognizing that a small gap may be required between the diffuser element and secondary fan to reduce the acoustical noise produced by the overall configuration. The diffuser element and the air conducting tube may be combined and further adapted in various ways to provide further optimization and enhanced performance.

Further optimization may be achieved by controlling the combined momentum and swirl at the input to the secondary fan such that the momentum vector(s) drive the secondary fan to achieve greater efficiency and performance. Such optimization may require a more complex diffuser element design, optimized for efficient swirl energy to kinetic

energy conversion, directional control of the momentum vector(s), reduced drag, and so on.

Further optimization may also be achieved by using a primary fan with an integrated stator on the output side. In this case $Output_{SP}$ will have less swirl (due to the straightening effect of the stator) and a lower flow rate (due to the drag effects of the stator) relative to a similar primary fan that does not have an integrated stator. These attributes can be used to enhance the performance of, and reduce the overall length of, a high performance series fan configuration with diffuser element since the requirement for swirl reduction in the area between the two fans will have been reduced by the integrated stator on the primary fan. However the reduced level of drag produced by the shorter air conducting tube between the two fans, and the smaller diffuser element, may be offset by the Incremental drag produced by the integrated stator on the primary fan.

A closely coupled high performance series fan with diffuser element, or dual redundant fan module, is ideally suited for the cooling of cabinets and other enclosures. Further, the excellent single stream performance under high static pressures makes it ideal for the impingement cooling of CPUs and other electronic components, as well as the impingement cooling of power heat sinks. The latter configuration may be referred to as a high performance series fan sink.

A loosely coupled or "push / pull" series configuration is depicted in Figure 25 (with reference to the following components and corresponding numbers for Figure 25 and Figure 26 only);

Component	*No.*	*Component*	*No.*
Primary Fan	300	Secondary Fan	302
Air Flow In	304	Electronic Components	306
System Cabinet	308	Air Flow Out	310

A loosely coupled series configuration may be designed to incorporate some of these operating parameters, however it will likely deliver sub-optimal performance relative to a closely coupled configuration using similar fans. A loosely coupled series configuration has a much larger distance and a much less efficient duct between the primary and secondary fans, as illustrated below. The result is a substantial loss of momentum before the airflow reaches the secondary fan.

The practice of relying on the electronic and other components to remove swirl may work to some degree, however it would be extremely difficult to lay out the components for the optimization of this function, and doing so may introduce volumetric inefficiencies in the design. Further, it would be extremely difficult to configure the components such that substantially all of the swirl will have been removed just as the airflow enters the secondary fan. Further, the optimized design, if it could be achieved, would change with the addition or modification of a single component within the air space between the two fans.

In contrast, a tightly coupled or modular series fan configuration operates with an optimized design that remains the same regardless of component layout within the system cabinet being cooled. While a change in components may affect the static pressure or load conditions, it will not affect the optimized design of the high performance series fan configuration. In other words the performance curve (i.e. static pressure / flow curve) for the high performance series fan configuration will remain the same regardless of the change in load curves – it is just the intersection of these curves (i.e. the operating point) that will change. The fact that the output of an optimized high performance series fan configuration may be plotted as a standard performance curve greatly eases the thermal design task since the operating point may be readily determined in the same way that one would determine the operating point for a single fan.

It is possible to combine some of the benefits of a tightly coupled series configuration with a loosely coupled series configuration by placing a diffuser element immediately prior to the secondary fan as depicted in Figure 26 (with reference to the following components and corresponding numbers for Figure 25 and Figure 26 only);

Component	*No.*	*Component*	*No.*
Primary Fan	300	Secondary Fan	302
Air Flow In	304	Electronic Components	306
System Cabinet	308	Air Flow Out	310
Diffuser Element	312		

The installation of a diffuser element at this point in the loosely coupled configuration will serve to remove substantially all of the swirl before the air enters the secondary fan, providing an increase in efficiency as described above.

A further analysis of equation (3) above reveals that the configuration may be more responsive to an increased level of power applied to the secondary fan relative to the primary fan. This is due to the fact that the impact of any incremental power applied to the secondary fan is enhanced beyond what one would normally expect from a single independent fan because of the increased momentum of the air entering the secondary fan. When operating independently, the momentum of the air flowing into and out of the secondary fan is completely generated by the secondary fan. When operating in a series configuration, however, the air flowing through the secondary fan has a residual momentum that has already been generated by the primary fan. This increases the efficiency of the secondary fan beyond that of an independent fan.

A further observed effect is that the primary fan is more sensitive (than the secondary fan) to the drag introduced by the diffuser element as noted in equation (3). This also indicates that the series configuration may be more responsive to increased power applied to the secondary fan rather than the primary fan.

It is therefore possible to take advantage of these effects, and increase the efficiency of the overall series fan configuration, by re-balancing the distribution of power such that more power is applied to the secondary fan than the primary fan. The result will be an increased output relative to an equal distribution of the same total power between the two fans. This principle may be applied to tightly coupled or loosely coupled series fan configurations. In practice it may be implemented by supplying a higher voltage to the secondary fan than the primary fan, or by utilizing a higher performance secondary fan and applying the same voltage to both fans, or through some other means.

It is important to note that although the preceding discussion has been limited to high performance series fan configurations with two fans, the principles taught herein may also be applied to configurations of three or more fans in various series combinations. As an example, a tightly coupled serial fan module may replace the primary fan in a loosely coupled configuration, resulting in a three (3) fan configuration with enhanced performance.

Further, multiple high performance series fan modules may be installed in parallel for greater airflow capacity and / or to provide multiple fault tolerant airflows. It has been previously noted that parallel single fan installations are not inherently fault tolerant since the failed fan presents an air leak that quickly disperses the pressure and airflow produced by the remaining fan(s). In contrast, a parallel installation of two or more high performance series fan modules *is* fault tolerant because each one of the series fan modules is inherently fault tolerant. The module that contains the failed fan will still continue to produce airflow and pressure, thereby preventing the leakage of air that is normally associated with a parallel fan installation. As an added benefit, the failed fan may be replaced on a scheduled rather than an urgent basis.

Parallel high performance series fan modules are ideal for many applications including system cabinet cooling and rack mount enclosure cooling. The former is particularly well suited for very low profile 1U and 2U (approximately 44mm and 88mm in height, respectively) server formats where the installation of larger diameter fans is impossible and performance and fault tolerance are essential. The latter configuration may be used to replace the parallel single fans commonly installed on a fan tray to form a high performance series fan tray.

A high performance series fan configuration operates in fault mode when one fan fails, and the remaining fan continues to create airflow. A controller may be configured to recognize and respond to this situation by increasing the power supplied to the remaining fan, thereby increasing the output during failure mode. In some applications that demand improved fault mode performance a unique offset series configuration provides a supplementary air inlet or air outlet that may be opened in the event of a fan failure to improve the efficiency of the remaining fan, while maintaining a consistent direction and rate of flow

Finally, the principles taught herein may be applied to larger fans and propellers to develop high performance fault tolerant automotive fans, e.g. for cooling and turbo-charging, innovative consumer products, such as vertical pole fans to de-stratify the air within a room, high performance fault tolerant industrial fans, e.g. for large air moving systems, propulsion systems, where the safety associated with a fault tolerant configuration cannot be underestimated, and other applications that may become obvious when the principles are understood. Further, the principles taught herein may also be applied to other gasses and fluids, e.g. for the development of pumps and marine propulsion systems, and other applications that may becomes obvious when the principles are understood.

Embodiments

Embodiments of the invention are described by way of example with reference to the drawings in which:

Figure 1 illustrates an inefficient series fan configuration,
Figure 2 illustrates an efficient series fan configuration with diffuser elements,
Figure 3 provides an overview of a high performance series fan configuration,
Figure 4 provides a side view of a high performance series fan configuration,
Figure 5 provides a side view of a high performance series fan in normal operation,
Figure 6 provides a front view of a high performance series fan with a control panel,
Figure 7 illustrates how a high performance series fan drawer may be withdrawn from a cabinet,
Figure 8 details the replacement of one of the series fans,
Figure 9 shows how two high performance series fan modules may be mounted in parallel,
Figure 10 shows a high performance series fan module with a supplementary air inlet and outlet,
Figure 11 provides a connection diagram for a high performance series fan controller,
Figure 12 illustrates a control algorithm for a high performance series fan controller in flow chart format,
Figure 13 provides a perspective view of a high performance series fan sink,
Figure 14 provides a section view of a high performance series fan sink,
Figure 15 illustrates a high performance series fan sink with the primary fan being replaced,
Figure 16 illustrates a high performance series fan sink with the secondary fan being replaced,
Figure 17 provides a perspective view of a high performance series fan tray,
Figure 18 provides a second perspective view of a high performance series fan tray showing further details of one of the high performance series fan modules,
Figure 19 illustrates a high performance series fan tray with the primary fan being replaced,
Figure 20 illustrates a high performance series fan tray with the secondary fan being replaced,

Figure 21 illustrates a high performance series fan tray controller operating in a fan failure mode,
Figure 22 illustrates a method for monitoring airflow through a high performance series fan module, and:
Figure 23 provides a perspective view of an alternatively configured high performance series fan tray.

FIG. 1 illustrates an inefficient series fan configuration with three independent axial cooling fans mounted such that the output from one fan becomes the input to the next fan in the series. In this case the output from primary fan 8 becomes the input to secondary fan 16, and in like manner the output from secondary fan 16 becomes the input to tertiary fan 17. Basic series fan configurations may be comprised of two or more axial fans configured in this manner.

An axial fan works best if it sees a substantially laminar flow, i.e. a flow with no or a controlled level of swirl, on the input side. This condition is met with a single fan since there is nothing on the input side to generate swirl. However this is not the case with a basic series configuration since the outputs of the primary fan 8 and secondary fan 16 (as with all axial fans) contain swirl as depicted by airflow with swirl 10 and second airflow with swirl 11. Therefore a basic series configuration is inefficient because the secondary, tertiary, and all subsequent fans will have a substantial swirl component in the input airflow.

In contrast, FIG. 2 illustrates an *efficient* series fan configuration with diffuser element 14 and second diffuser element 15 inserted between primary fan 8 and secondary fan 16, and secondary fan 16 and tertiary fan 17, respectively.

The result of inserting diffuser element 14 between primary fan 8 and secondary fan 16 is to convert the input seen by secondary fan 16 from airflow with swirl 10 to reduced swirl airflow 12, thereby increasing the efficiency of secondary fan 16 to a level approaching that of primary fan 8. Likewise, second diffuser element 15 will convert the input seen by tertiary fan 17 from second airflow with swirl 11 to second reduced swirl airflow 13, thereby improving the efficiency of tertiary fan 17.

Diffuser element 14 and second diffuser element 15 may be comprised, for example, of filter material or a number of vanes or tubes mounted in the path of the air and configured to reduce swirl and direct the airflow into downstream fan, as illustrated by alternative second diffuser element 15a. Further, the vanes or tubes may be configured to leave a certain level of residual swirl in the airflow in order to (1) flow more easily past the stationary fan blades of a the downstream fan and/or (2) create a set of input conditions that would allow the downstream fan to operate more efficiently, at above design conditions, rotating faster than normal for a given input power level. In certain applications it may be beneficial to combine diffuser element 14 and second diffuser element 15 with other functions such as a heat exchanger to add or remove heat from the airflow, or an Electro-Magnetic (EM) shield to substantially prevent the passage of EM waves through the fan opening. While the number of different diffuser element designs and their related efficiencies and functionalities is vast, the principle of reducing swirl to improve the efficiency of the secondary or downstream fan remains the same.

While diffuser element 14 and second diffuser element 15 may be primarily designed to reduce swirl, they will also add an impedance to the airflow that will add to the system head and reduce the efficiency of the system. This becomes a trade-off that must be balanced against the positive effects of installing a diffuser element between two fans in series. In general, however, the overall effect of installing a diffuser element is positive since the impact of the reduced swirl far outweighs the incremental system head. In some applications the pressure drop across the diffuser element may be monitored and used to measure the airflow through the diffuser element.

FIG. 2 also illustrates the impact of a fan failure. If primary fan 8 fails, then secondary fan 16 and tertiary fan 17 will continue to draw air through the assembly and "push" it in the same direction, i.e. combined airflow 22 will continue to flow in the same direction, and no external baffling changes will be required. A similar result will occur if secondary fan 16 or tertiary fan 17 fails. This ability to continue to provide airflow in the same direction despite the loss of a fan is the primary inherent advantage of a series fan configuration.

In the event of a primary fan 8 failure, the fan blades may continue to rotate or they may remain fixed or "locked" – depending on the nature of the failure. However, in the case of primary fan with variable pitch blades 8a, primary fan blade 9 will remain in an oblique

position during normal operation (i.e. while rotating in the direction defined by arrow 7) and then return to coaxial position 9a in the event of a failure. Since coaxial position 9a aligns the fan blade with the airflow, it will present a far lower input impedance as seen by secondary fan 16, therefore contributing to increased efficiency during a primary fan with variable pitch blades 8a failure relative to an primary fan 8 (i.e. fixed fan blade) failure. It follows that a secondary fan 16 with similar variable pitch blades would also contribute to greater efficiency during the failure mode as it would present a lower output impedance as seen by primary fan 8.

Although the *direction* of airflow will remain consistent in a series fan configuration with a single fan failure, the *volume* of airflow will be reduced if the remaining fan(s) continue to operate at the same speed. This is an acceptable situation only if the volume of airflow does not fall below the minimum required to dissipate the heat generated in the cabinet or by the components being cooled. In practice a control system may be required to sense the fan failure and adjust the remaining fan speed accordingly, in order to ensure that this minimum airflow requirement is met until the defective fan can be replaced. This type of control can be easily implemented since (1) many fans today are available with fault sensors to indicate an impending failure / total failure and (2) fan speed can be easily controlled by varying the input voltage, at least for DC fans, or by using some other type of fan speed controller.

During normal operation, primary fan 8, secondary fan 16, and tertiary fan 17 may all be operating at less than full rpm to produce the required combined airflow 22. The lower rpm will reduce the noise produced by each fan and also extend the life of each fan. Should the controller sense an impending or actual failure in one of these fans, then the. The user may then be alerted to replace the defective fan on a scheduled rather than an urgent basis. Similarly, if the airflow is impeded by a clogged air filter or some other obstacle, then the power applied to the fans may be increased to the point where combined airflow 22 remains the same.

A series configuration of "n +1" fans configured with intermediate diffuser elements, as described above, will be tolerant to the failure of one fan where "n" is the total number of fans whose combined flow is required to meet the cooling requirements of the system or component(s) being cooled. FIG. 2 illustrates an example where "n" = 2, and "n + 1" = 3

fans in total. Actual configurations may include 2, 3 or more fans depending on cooling requirements. The remainder of this document will deal with high performance series fans with diffuser elements configured with two fans for reasons of simplicity, however it should always be noted that additional fans may be added to these representative series configurations. Further, it should be noted that multiple fans could be added to provide increased performance while preserving an n + 1 redundancy and providing a fault tolerant configuration.

It is also possible that multiple series fans with diffuser or flow modification elements may be installed in parallel to meet demanding cooling requirements. In this case, there is no need for the movable baffles normally associated with parallel configurations since each independent high performance series fans with diffuser element assembly is fault tolerant and will not allow the back flow or "leakage" of air in the event of a fan failure. These configurations may be used to meet very high airflow requirements, to produce independently directed airflow streams, or where space considerations limit the number of fans that may be mounted in a series.

Series fans with flow modification element, or high performance series fans, may be configured to allow a defective fan to be replaced without having to shut down the system or components being cooled - commonly referred to as "hot swapping" the fans. This is made possible by the fact that high performance series fans 1 may be configured to fit in a sliding "drawer" that can be pulled away from the cabinet without interrupting the airflow, as illustrated in FIG. 3. In this case secondary fan 16 is being replaced while sliding drawer 2 is in the "out" position. Sliding drawer 2 may then be returned to the "in" position without affecting system operation or necessitating a system shut down. A control system may be configured to detect the fan failure, alert the user, detect the presence of a new and fully functional secondary fan 16, adjust the power applied to both primary fan 8 and secondary fan 16 to maintain a controlled airflow throughout the process, and then reset the lights on control panel 30 to reflect normal operation. Note that diffuser element 14 could also be replaced while the sliding drawer 2 is in the "out" position, again without affecting system operation. Finger guard 6 has been added to the configuration for safety reasons.

FIG. 4 provides further detail in a side view of high performance series fans 1 mounted in sliding drawer 2. Primary fan 8 and secondary fan 16 are mounted co-axially in sliding drawer 2 such that the air flowing from primary fan 8 flows through diffuser element 14 and directly into secondary fan 16. Sliding drawer 2 slides into and out of internal sleeve 3 as depicted by drawer movement arrow 18. Sliding drawer 2 requires a minimum opening in cabinet 4, taking less cabinet wall space than a parallel configuration and making it easier to maintain the integrity of an EM shield. In certain applications diffuser element 14 may be configured as an integral part of the EM shield.

Internal sleeve 3 has at least five distinct functions; (1) to provide a means to mount sliding drawer 2, and therefore high performance series fans with diffuser element 1, on cabinet 4, (2) to provide a means to allow sliding drawer 2 to slide "in" or "out", (3) to support sliding drawer 2 whilst in the "in" or "out" position, (4) to provide baffling such that combined airflow 22 *only* exits the assembly through the open end of internal sleeve 3, and (5) to provide, in combination with sliding drawer 2, a contained channel for the air flowing through high performance series fans 1.

The latter function is particularly important since the length and geometry of the contained air channel between primary fan 8 and diffuser element 14 may be configured to provide a pre-determined level of natural decay of swirl in the airflow before it enters diffuser element 14. This natural decay of swirl may be enhanced by providing multiple corners within this portion of the contained air channel, for example by configuring the air channel with a square or hexagonal cross section. In certain applications, in particular those using a primary fan 8 having stator blades, the this portion of the contained air channel may be shortened while providing the same overall effect since some of the swirl will have already been removed by the stator blades.

Similarly the length and geometry of the contained air channel between primary fan 8 and diffuser element 14, and diffuser element 14 and secondary fan 16, may be configured to reduce the acoustical noise produced by high performance series fans 1. As an example, a short contained air channel with smooth walls between diffuser element 14 and secondary fan 16 may be configured to reduce acoustical noise, even though it may not necessarily be required to further reduce swirl in this region.

Flange 21 may be used to secure internal sleeve 3 to cabinet 4 with machine screws, or through some other suitable means. Latch 19 may be used to hold and seal tab 20 against flange 21, i.e. to hold sliding drawer 2 in the "in" position, until released. Back lip 5 extends outward from the normal geometry of sliding drawer 2 to prevent the accidental removal of sliding drawer 2 by coming to rest against an extended portion of flange 21, when sliding drawer 2 is in the full "out" position. A means may be provided to completely remove sliding drawer 2 from internal sleeve 3, when and if required.

In some applications diffuser element 14 may be configured as a diffuser, to reduce swirl in the airflow leaving primary fan 8, and as a filter, to substantially remove unwanted particulate from the airflow. In these cases diffuser element 14 should be selected to optimize both functions, in combination with the length and geometry of the contained air channel between primary fan 8 and diffuser element 14, as described above, while introducing a minimal incremental system head.

Alternatively, an air filter optimized for removing particulates may be mounted between finger guard 6 and primary fan 8, leaving the diffuser element 14 to be fully optimized for the reduction of swirl. In these configurations diffuser element 14 may be a screen, a laminar flow element consisting of a number of round, square, hexagonal, or alternatively shaped tubes mounted co-axially with the fans, a series of flow directing vanes, or some combination thereof. Further, diffuser element 14 may be configured with an air funnel at the entry point to each tube, and with the funnel openings directed / skewed towards the source of the air as it comes off the blades of primary fan 8. Regardless of configuration, the flow related objective of diffuser element 14 is, in combination with the length and geometry of the contained air channel between primary fan 8 and diffuser element 14, to reduce swirl in the airflow leaving primary fan 8, and before it enters secondary fan 16, while introducing a minimum amount of incremental back pressure, thereby contributing to the overall efficiency of the high performance series fans 1.

Primary fan 8 and secondary fan 16 may rotate in the same or different directions. This aspect of the configuration will be somewhat dependent on the cost, performance, and acoustical objectives associated with a given application, as a pair of standard fans that rotate in the same direction may be less expensive than a pair of counter-rotating fans,

or a counter-rotating fan module. Also, any efficiency gained by having counter-rotating fans should be weighed against the service cost of stocking two types of spares.

FIG. 5 shows high performance series fans 1 in operation. In this case sliding drawer 2 has been moved "in" such that finger guard 6 is flush with the outside of cabinet 4. Sliding drawer 2 slides within the internal sleeve with sliding interfaces at flange 21 and back lip 5. Alternatively, sliding drawer 2 may be configured to slide on rails or some other suitable means.

Sliding drawer 2 is prevented from moving farther into cabinet 4 by tab 20 (top and bottom) when it interfaces with the outer edge of flange 21.Sliding drawer 2 is then held in place by latch 19. In some cases an aesthetic cover may be configured to snap onto the outside of sliding drawer 2, once in place, to improve the appearance of the cooling module. Further, the aesthetic cover would provide visual access to the control panel so that the operation of high performance series fans 1 could still be easily monitored.

As in FIG. 4, cooling air flows efficiently through primary fan 8, diffuser element 14, and secondary fan 16 to provide combined airflow 22. It is important to note that the direction of combined airflow 22 remains consistent whether one or both of primary fan 8 and secondary fan 16 is / are operational. This precludes the requirement for any incremental baffling to ensure that the direction of combined airflow 22 remains consistent in the event of a fan failure.

In the event of a primary fan 8 failure, combined airflow 22 will continue to flow *through* primary fan 8 and into secondary fan 16 – i.e. the airflow will not escape through primary fan 8. Likewise, in the event of an secondary fan 16 failure, combined airflow 22 will continue to flow *through* secondary fan 16 and into cabinet 4 – i.e. the airflow will not escape through secondary fan 16. This precludes the requirement for specialize baffling to prevent combined airflow 22 from escaping through the defective fan.

The last two paragraphs highlight a very important characteristic of the series fan configuration – no baffling is required to accommodate a failed fan scenario. This contrasts sharply with the parallel fan configuration where substantial baffling is required to prevent the loss of air through the defective fan and to keep the direction of airflow

consistent in the event of a fan failure. As a result, high performance series fans are very compact, and they may be configured as a stand-alone cooling module that does not requires any further baffling.

Primary fan 8 may need to be rated at a higher capacity than secondary fan 16 to compensate for the added backpressure introduced by diffuser element 14 and secondary fan 16, if and when secondary fan 16 is defective and / or stationary. Conversely stated, secondary fan 16 may be rated at a lower capacity than primary fan 8 because it will not "see" the same incremental causes of backpressure. In practice both fans may be of the same rating, but should they be so configured that the ratings match the higher rating required by primary fan 8. This will ensure that combined airflow 22 will always exceed the minimum required regardless of whether one or both fans is / are operational.

During normal operation primary fan 8 and secondary fan 16 may run at less than full rpm as long as combined airflow 22 meets the cooling requirements for the application at hand. Further, the total power applied to the system may be re-balanced asymmetrically, with more power being applied to the secondary fan in order to take advantage of the fact that secondary fan 16 runs more efficiently than primary fan 8, therefore improving the overall efficiency of the system. The configuration will be very responsive to a fan failure since the remaining fan is already running, albeit at a lower rpm, and it is much faster to ramp up from partial to full rpm than it is to go from stopped to full rpm.

It can be deduced from FIG. 5 that the size of the opening in cabinet 4 will be only slightly larger than the size of primary fan 8. In a parallel configuration the opening would be approximately twice this size since the two fans would be mounted side-by-side. Further the volume of space required in cabinet 4 will be much smaller than a parallel configuration since no extra internal baffling will be required. This 2:1 reduction in the size of the opening combined with the much smaller internal volume requirement represents a major benefit of the series configuration from a system designer's perspective.

In simple configurations, high performance series fans 1 may be implemented without a controller by using two fans, each of which is capable of providing the full combined

airflow 22 required for the application at hand. Under normal operating conditions combined airflow 22 will actually exceed the minimum requirement, keeping the load cooler than necessary. A fan failure can be tolerated since the remaining fan will already be running, and is capable of carrying the load. As described above, no further baffling is required since the fans are in series. A simple indicator light will flag the operator to replace the defective fan.

In other configurations, where power consumption, precise cooling, and / or acoustic management are important requirements, a controller may be used to provide a controlled airflow during normal operation and in the event of a fan failure. The controller may be installed behind control panel 30, as shown in FIG. 6. This drawing also illustrates the full extent of tab 20 as seen around the perimeter of the unit, and the front face of finger guard 6. Control panel 30 contains indicator lights 32 to alert the user regarding the operation of primary fan 8, secondary fan 16, and diffuser element 14 (reference FIG. 5). The controller may also be adapted to communicate with other systems for remote monitoring and control.

An aesthetic cover may be affixed over the entire front face of high performance series fan 1, providing that airflow is not impeded to the degree that it will affect cooling performance. In most cases indicator lights 32 will need to be visible through the aesthetic cover so that the operator can respond to a fan problem, however this may not be an absolute requirement in situations where the operator may be initially alerted through some other means, for example through software and a remote monitor. In the latter case the operator, once alerted to the problem, could remove the aesthetic cover and visually inspect indicator lights 32 to determine which fan is defective.

Fans are readily available with sensors for failure, or degradation in performance that might indicate imminent failure. This information may be used to inform the controller to increase the speed of the other fan in order to continue to provide the required airflow. The controller can also use the same information to illuminate the appropriate indicator lights 32, alerting the operator to take action. Indicator lights 32 may be activated in several different modes, e.g. steady, flashing, red yellow or green, to communicate certain information and the level of severity of the problem to the user.

Under normal operation each fan may be running at less than maximum rpm to extend life, reduce noise, and to allow for an immediate increase in speed should the other fan fail. It is possible that one fan may be left idle (i.e. not running) during normal operation, however in practice it may be better to leave both fans running to some extent in order to (1) continually ensure that they are both operational (2) minimize any "ramp up" time in the event of a failure and (3) reduce any unnecessary static loads or sources of backpressure during normal operation.

FIG. 7 illustrates how high performance series fans 1 may be withdrawn from cabinet 4 to allow for the inspection and / or replacement of a faulty component. Note that finger guard 6 has been removed in this diagram for illustrative purposes only, and that this would not normally be the case when servicing the unit.

FIG. 8 provides a top view of high performance series fans 1, and illustrates the method of replacing a defective fan without shutting down the system, commonly referred to as "hot swapping" the fans. In this scenario secondary fan 16 is defective, and this information would have been conveyed to the user through indicator lights 32.

The first step in replacing defective secondary fan 16 is to pull out sliding drawer 2 until it is fully extended, as depicted by drawer extension arrow 42. At this point back lip 5 will rest against the internal edge of flange 21 to prevent further forward movement of sliding drawer 2. Internal indicator lights 33 may be used as a secondary check to ensure that the correct (faulty) fan is being removed.

Once sliding drawer 2 is in the fully extended position, secondary fan 16 may be removed by sliding it sideways, to the right, and disconnecting internal power and control cable 44 from internal power and control receptacle 46. FIG. 8 shows secondary fan 16 partially removed with approximately 30% of its width already beyond the right side of sliding drawer 2. Note that secondary fan 16 is completely outside of and can slide clear of cabinet 4. It can be seen that diffuser element 14 and primary fan 8 could be similarly removed without interfering with cabinet 4.

Primary fan 8 remains running as secondary fan 16 is being removed and replaced, and may be running at a higher RPM, as determined by controller 40, so that combined

airflow 22 remains at or above the minimum airflow required to cool the components contained within cabinet 4. Note that the direction of combined airflow 22 will not change, as it remains contained and directed by internal sleeve 3, precluding the need for any change in baffling when running with only one fan. It can be seen from FIG. 8 that diffuser element 14 and primary fan 8 may be similarly removed without affecting the direction of the combined airflow 22. All of these operations can be completed without shutting down the system contained in cabinet 4.

Referring back to the scenario at hand, a new secondary fan 16 may be set in place in sliding drawer 2, and the internal power and control cable 44 may be re-connected to internal power and control receptacle 46. Controller 40 may be configured to recognize that secondary fan 16 has been replaced, and that it is operational, and to adjust the speed of primary fan 8 and secondary fan 16 accordingly. Sliding drawer 2 can then be pushed back into cabinet 4 such that finger guard 6 and control panel 30 are flush with the outside of cabinet 4. Indicator lights 32 may then be monitored by the operator for further problems. Indicator lights 32 and controller 40 may also be interfaced with the system in cabinet 4 to alert the operator through other means such as a remote system monitor.

Sliding drawer 2 may be configured to accommodate standard sized fans available from a variety of manufacturers, e.g. 120 mm, 92mm, or 40 mm fans. These fans are readily available in a variety of thicknesses that loosely correspond to a range of CFM ratings, i.e. the thicker fans generally have a higher CFM rating for a given fan diameter. It follows that sliding drawer 2 may be configured to accept the thickest fan in a particular size range, and that slimmer or lower capacity fans may be accommodated by installing the fan in conjunction with a "shim" ring that takes up the extra space and holds the fan securely in place. This approach allows a standard size sliding drawer 2 to accommodate a variety of fan capacities, and also provides a convenient upgrade path since the shims may be removed or replaced with thinner shims to allow the installation of higher capacity fans. This approach can be used to provide additional cooling, when required, without replacing the entire cooling subsystem.

In some applications it may be necessary to provide a fixed baffle 48 inside cabinet 4 to ensure that re-directed combined airflow 49 is appropriate for the application. This fixed

baffle 48 will need to interface with internal sleeve 3 to prevent air leakage, however it will remain fixed in the event of a fan failure.

FIG. 9 shows how two high performance series fan modules may be mounted in parallel for increased airflow. Parallel baffle 50 may be configured to interface with top inner sleeve 3a and bottom inner sleeve 3b to contain the output from both compact series fan assemblies, and produce total combined airflow 54. Sealing cap 52 may be positioned between the two assemblies to improve the airflow and to prevent any leakage of air in this area. Sealing cap 52 may be configured with a cone shaped cap that protrudes downstream, or some other feature, to increase the efficiency of the airflow.

It is important to note that even though this is a parallel configuration of series fan assemblies, it does not require any of the specialized baffling normally associated with this type of installation. This is because each one of the high performance series fans with diffuser element assemblies is independently fault tolerant, and prevents the back flow of air in the event of a fan failure. In other words, each series fan assembly will *always* contribute to total combined airflow 54, and will *not* allow a portion of combined airflow 54 to leak back out to the ambient air around cabinet 4, even in the event of a single fan failure.

The parallel configuration of high performance series fan modules also provides more flexibility in the event of a fan failure. In this case a controller may be configured to speed up three additional fans, rather than just one in a non-parallel installation, to maintain a constant total combined airflow 54. It follows that parallel configurations with more than two high performance series fans with diffuser element assemblies will have an even greater ability to respond to a single fan failure.

FIG. 10 shows a high performance series fan module configured with a supplementary air inlet and outlet to improve airflow in the event of a fan failure.

Under normal operation, air inlet baffle 70 and air outlet baffle 72 will direct the output from primary fan 8 and diffuser element 14 through secondary fan 16 to form combined airflow 22, as previously described. Combined airflow 22 is further directed through air

funnel 74 which may have an opening size that approximates the opening size of the fans.

In the event of a primary fan 8 failure, air inlet baffle 70 may be moved to position 70a to reduce the input impedance seen by, and therefore increase the flow of air into, secondary fan 16. Outlet baffle 72 may remain in place to ensure that no air leaks from the output side to the input side of secondary fan 16. Combined airflow 22 will be comprised solely of the output from secondary fan 16, part of which will flow through the defective primary fan 8 and another part of which will flow through the open inlet baffle 70a.

Conversely, in the event of an secondary fan 16 failure, air outlet baffle 72 may be moved to position 72a to reduce the output impedance seen by, and therefore increase the flow of air out of, primary fan 8. In this case inlet baffle 70 will remain in place to ensure that no air leaks from the output side to the input side of primary fan 8. Combined airflow 22 will be comprised solely of the output from primary fan 8, part of which will flow through the defective secondary fan 16 and another part of which will flow through the open outlet baffle 72a.

Inlet baffle 70 and outlet baffle 72 may be configured to operate automatically, based on pressure differentials, or to be controlled by controller 40 (reference FIG. 8). In the former case a higher relative pressure between primary fan 8 and secondary fan 16 would cause outlet baffle 72 to move to position 72a, and a lower relative pressure between the same fans would cause inlet baffle 70 to over to position 70a. In the latter case controller 40 may be used to control the position of the baffles in response to a failing or defective fan. In all cases the action taken serves to relieve the pressure differential and improve the flow of air through the configuration. However the use of the controller provides greater flexibility and does allow for certain load sharing scenarios between the two fans that might cause temporary pressure differentials between the fans that might otherwise be interpreted as a defective fan situation.

It is important to note that air inlet baffle 70 and air outlet baffle 72 may be configured, in conjunction with air funnel 74 and controller 40 (reference FIG. 8), such that the direction and rate of combined airflow 22 will remain constant even in the event of a fan failure.

This precludes the requirement for any further baffle changes within cabinet 4 in the event of a fan failure, meaning that the configuration may still be supplied as a standalone module that provides fault tolerant cooling.

It is also important to note that the use of air inlet baffle 70 and air outlet baffle 72 still allows for the replacement of a defective fan or filter element / diffuser while the system is running. This is because air inlet baffle 70 and air outlet baffle 72 have been configured to not interfere with the normal removal and replacement of the fan and filter element / diffuser element while sliding drawer 2 is in the "out" position as previously described.

Primary fan 8 and secondary fan 16 may both be mounted with axis parallel to combined airflow 22 as shown in FIG. 10. Alternatively, primary fan 8 and secondary fan 16 may both be mounted at a slight angle to the desired combined airflow 22, and not necessarily in a coaxial fashion, in order to improve the smooth flow of air between primary fan 8 and secondary fan 16. In this case inner sleeve 3 and air funnel may be adaptively re-configured to ensure that combined airflow 22 flows in the desired direction.

FIG. 11 provides a connection diagram for high performance series fan controller 40. Controller 40 may be configured to receive its primary input from cooled component(s) 62, upon which the output of high performance cooling fan module 1, i.e. combined airflow 22, impinges. This primary input may be comprised of information such as the temperature of cooled component(s) 62, the rate of airflow around cooled component(s) 62, and the current and / or anticipated workload on cooled component(s) 62. Information regarding the anticipated workload on cooled component(s) 62 would allow controller 40 to proactively respond to a corresponding change in heat dissipation requirements by changing the speed of primary fan 8 and / or secondary fan 16.

Controller 40 may also be configured to receive input from airflow sensor 60. Airflow sensor 60 provides information regarding the rate of combined airflow 22, and this information may be used by controller 40 to test for appropriate responses to changes in input to primary fan 8 and / or secondary fan 16. A non-appropriate response to such an input may be used by controller 40 to determine that there may be a fault with diffuser

element 14 or one of the fans. For example, controller 40 may determine that combined airflow 22 cannot be maintained above a threshold level and may deduce that (1) this problem may be caused by a seriously clogged diffuser element 14, especially if it has a secondary function as a filter, or, in the worst case, that (2) both fans may have failed or are failing simultaneously. The user would be alerted to take immediate action in either case, and a graceful shutdown procedure could be initiated if either situation persists for an unacceptable period of time.

Controller 40 may also be configured to receive input from position sensors 64, which inform controller 40 regarding the correct installed position of primary fan 8, diffuser element 14, and secondary fan 16. In the case of the fans, this information may be combined with input from combined control and monitor wires 66 to determine that the fans are installed correctly and operating efficiently. The combined control and monitor wires may be used to supply a control voltage to the fans, monitor current draw, and in some cases monitor other information such as rpm, output temperature, or output flow rate.

Position sensors 64 may further contain a physical feature that precludes the incorrect installation of primary fan 8 and secondary fan 16, i.e. prevents an accidental installation that would cause air to flow in the wrong direction. Such an incorrect installation could cause immediate damage to the components being cooled.

The information provided by combined monitor and control wires 66 may be used by controller 40 as leading indicators of potential fan failure. As an example, a drop in rpm for a given voltage input may indicate that a bearing is failing. Controller 40 may initially respond by increasing the voltage input to that fan, and alerting the user to the problem. Controller 40 may ultimately respond by shutting down the defective fan and changing the load over to the alternative fan if the problem persists. Most importantly, the information allows the controller to make proactive responses to an impending problem before cooled component(s) 62 becomes overheated.

Controller 40 may communicate with the user through control panel 30, containing indicator lights 32a, 32b, and 32c, which may be used to indicate the status of primary fan 8, diffuser element 14, and secondary fan 16 respectively. Any commonly

understood indicator algorithm may be used, for example green meaning normal operation, yellow meaning that a component should be replaced due to sub-optimal performance or impending failure, and red or flashing red used to indicate that a component has failed. Note that a failed fan does not mean that high performance cooling fan module 1 is not operating; it simply means that the system is only running with one fan and has no ability to respond to a further fan failure. Therefore the failed component must be replaced immediately to avoid potential problems.

As an example, controller 40 may be used to monitor the amount of time that diffuser element 14 is in use, and to activate the appropriate indicator light 32 should the "in use" time exceed a recommended maximum. This will alert the operator to replace diffuser element 14. The appropriate position sensor 64 in may be used to automatically reset the "in use" timer back to zero. This algorithm would be particularly useful in applications where diffuser element 14 is configured as a combined filter / diffuser element.

Controller 40 may also communicate with the user through a second redundant set of internal indicator lights 33 (reference FIG. 8). These lights may be more visible to the user or service technician when the fans are being replaced, and therefore they will serve as a safeguard to prevent the accidental removal of a correctly operating fan. Such a mistake would leave only the defective fan in place, potentially causing immediate damage to cooled component(s) 62. Controller 40 may use an audible emergency signal to instantly warn the user of such a dangerous situation.

FIG. 12 presents a control algorithm for a high performance series fan controller, in flow chart format.

The fundamental purpose of the controller is to keep cooled component(s) 62 (reference FIG. 11) within a defined control temperature range, despite changes on workload that might affect the heat dissipated by cooled component(s) 62. Therefore the first task in each control cycle is to check for anticipated changes in workload as outlined in first decision triangle 80. This information may come from the operating system associated with cooled component(s) 62. An increase in workload would cause the controller to increase the output CFM control point, and a decrease in workload would cause the controller to decrease the output CFM control point, perhaps after some delay period, as

indicated by first control box 86. The controller would proceed directly to second decision triangle 82 should there be no anticipated changes in workload.

At second decision triangle 82 the controller will check to ensure that cooled component(s) 62 (reference FIG. 11) is operating within its defined control temperature range. Should this not be the case, then the controller will adjust the output CFM control point to raise or lower the temperature of cooled component(s) 62 as required. However under normal operation, when no adjustment is required, the controller will proceed directly to third decision triangle 84.

At third decision triangle 84, the controller checks to ensure that the output CFM, i.e. combined airflow 22 (reference FIG. 11), is at the output CFM control point. Should there be a discrepancy that lies outside of the acceptable control range, then the controller will immediately investigate to determine the cause of the problem. As an example, secondary fan 16 (reference FIG. 11) may have suffered a drop in rpm given the same input parameters, a possible leading indicator of impending fan failure. The controller would then proceed to take corrective action by adjusting the inputs to secondary fan 16 and notifying the user through indicator lights 32 (reference FIG. 11).

Under normal circumstances the output of the high performance cooling fan module will be at the required constant output CFM control point and no corrective action will be required. In this case the controller loops back to first decision triangle 80 to repeat the above control cycle once again.

While operating normally, the controller may actually change the speed of both fans slightly on a regular timed basis. These subtle changes in rpm will prevent any lasting beat frequencies that might occur if the fans are left running at a constant rpm for any length of time.

Interrupts may be used at any time to alert the controller regarding a situation that requires immediate attention. Examples may include a locked rotor ("0" rpm with a full normal input) or perhaps a dislodged fan. In these cases the controller must take immediate action to preserve a constant CFM output, thus keeping the cooled component(s) at the required operating temperature.

FIG. 13 provides a perspective view of high performance series fan sink 100. Primary fan 8 and secondary fan 16 are configured in series to draw inlet airflow 108 into high performance series fan module 106, and push it into heat sink 102 where it divides into right outlet airflow 110 and left outlet airflow 112. Primary fan 8 and secondary fan 16 may be obliquely mounted on heat sink 102 at a variety of angles such the diagonal of the fans substantially covers the width of heat sink 102 and provides airflow through substantially all of the channels within heat sink 102. Air is retained within the confines of heat sink 102, such that it flows through and only exits at the open ends of heat sink 102, by baffle 104.

Baffle 104 may be configured to hold high performance series fan module 106 at a distance above heat sink 102, while preventing the leakage of air at the interface between baffle 104 and high performance series fan module 106, to improve the dispersion of air throughout heat sink 102. Further, baffle 104 may be configured to expand the opening of high performance series fan module 106 such that covers substantially all of the width of heat sink 102, allowing smaller series fan modules 106 to be used effectively with larger heat sinks 102.

Inlet airflow 108 is drawn through finger guard 122, into primary fan 8, through diffuser element 14, into secondary fan 16, and then pushed through heat sink 102 and exhausted as right outlet airflow 110 and left outlet airflow 112. Alternatively, the direction of airflow may be reversed such that right outlet airflow 110 and left outlet airflow 112 become the inlet airflows, and the air is exhausted through finger guard 122 at inlet airflow 108, which becomes the exhaust. However the former configuration, as illustrated in FIG. 13, provides for an impingement air flow on heat sink 102, and this can be directed at the area of maximum heat flux on heat sink 102 for enhanced cooling efficiency.

Control module 120 controls the operation of high performance series fan sink 100. Primary fan indicator light 122 and secondary fan indicator light 124 indicate the operating status of primary fan 8 and secondary fan 16 respectively. Control module 120 may be configured to sense the failure of primary fan 8 or secondary fan 16 and increase the power to secondary fan 16 or primary fan 8, respectively, to maintain a

relatively constant right outlet airflow 110 and left outlet airflow 112 during a single fan failure. Further, control module 120 may be configured to be responsive to a range of different backpressures to provide a relatively constant right outlet airflow 110 and left outlet airflow 112 over a range of operating conditions, or for a variety of heat sinks 102.

FIG. 14 provides a section view of high performance series fan sink 100. High performance series fan module 106 contains primary fan 8, diffuser element 14, and secondary fan 16. High performance series fan module 106 may be configured as a module that contains all of these components and holds them at the appropriate location, or alternatively as a standardized sub-assembly that only contains diffuser element 14 and is adapted to be bolted or otherwise fastened between two industry standard fans of similar geometry, e.g. two 120 mm or 40 mm fans.

Primary fan 8 is separated from diffuser element 14 by a first distance, and diffuser element 14 is further separated from secondary fan 16 by a second distance. The purpose of the first distance between primary fan 8 and diffuser element 14 is to reduce the swirl component of the airflow exiting from primary fan 8 through natural swirl decay, with a longer channel generally resulting in an increased level of natural swirl decay. The first distance may be reduced by configuring the internal geometry of the airflow channel to increase the rate of natural swirl decay, e.g. by using a square or octagonal internal cross section and/or by incorporating ridges, spines, or other surface features along the interior walls of the airflow channel, thereby reducing the overall length of high performance series fan module 106. The first distance may be further reduced by selecting a primary fan 8 having an integrated stator on the outlet side, thereby providing some level of swirl decay before the airflow leaves primary fan 8.

The purpose of diffuser element 14 is to complement the natural swirl decay accomplished within the first distance, i.e. between primary fan 8 and diffuser element 14, by further reducing the swirl component of the airflow before it enters secondary fan 16. This will increase the efficiency of secondary fan 16.

The purpose of the second distance between diffuser element 14 and secondary fan 16 is to reduce the acoustical noise produced by high performance series fan module 106. The small gap between the two components also provides sufficient space to mount a

pressure sensor, and this signal may be compared to the signal produced by another pressure sensor located on the upstream side of diffuser element 14 to provide an indication of flow rate through high performance series fan module 106.

Thermal load 130 may be in thermal communication with the bottom of heat sink 102, and may be optimally positioned such that area of highest heat flux (i.e. the hottest portioOn of heat sink 102) is immediately below the impinging airflow. Heat may then be removed through forced convection as the air flows through heat sink 102 and exits as right outlet airflow 110 and left outlet airflow 112, as previously described. Control module 120 may be configured to maintain a constant temperature of thermal load 130, a constant right outlet airflow 110 and left outlet airflow 112, or some combination of these and / or other control parameters.

FIG. 15 illustrates high performance series fan sink 100 as primary fan 8 is being replaced. A defective primary fan 8 may be removed while thermal load 130 (reference FIG. 14) remains active since control module 120 may be configured to increase the power applied to secondary fan 16 during the primary fan 8 outage, and until primary fan 8 has been replaced, in order to maintain a relatively constant right outlet airflow 110 and left outlet airflow 112 (reference FIG 14). Control module 120 may also be configured to detect the re-insertion of a new primary fan 8, and may then re-apply power to both fans in a controlled fashion to optimize the performance of high performance series fan module 106, as previously described.

FIG. 16 illustrates high performance series fan sink 100 with secondary fan 16 being replaced. A defective secondary fan 16 may be removed while thermal load 130 (reference FIG. 14) remains active since control module 120 will increase the power applied to primary fan 8 during the secondary fan 16 outage, and until secondary fan 16 has been replaced, in order to maintain a relatively constant right outlet airflow 110 and left outlet airflow 112 (reference FIG 14). Control module 120 may also be configured to detect the re-insertion of a new secondary fan 18, and may then re-apply power to both fans in a controlled fashion to optimize the performance of high performance series fan module 106, as previously described.

FIG. 17 provides a perspective view of high performance series fan tray 200, which may be configured with a single row of high performance series fan modules, as shown, or multiple rows of high performance series fan modules. Further, a single row of high performance series fan modules may be configured as a partial fan tray that may be mounted from the front of a rack system, and possibility combined with a similar fan tray mounted from the back of the same system to provide flexible and expandable cooling solutions. Further, high performance series fan trays 200 may be may be mounted horizontally to produce a vertical airflow, or vertically to produce a horizontal airflow. Finally, one or more high performance series fan modules may be added to an existing fan tray, using a traditional array of single axial fans in parallel, to increase performance and add a measure of fault tolerance to an existing installation.

Each high performance series fan module within high performance series fan tray 200 may be configured independently. For example, one module may be configured with a duct to provide direct cooling for one or more components within the system, and another module may be configured to actively exhaust air from the same or different component(s). Other modules may be configured to provide a more general flow of air within the system.

The high performance series fan tray 200 depicted in FIG. 17 includes three high performance series fan modules, 106a, 106b, and 106c, that draw inlet airflows 108a, 108b, and 108c, respectively, to produce outlet airflows 110a, 110b, and 110c, respectively. Control module 120 may be configured to monitor and control high performance series fan modules 106a, 106b, and 106c, and outlet airflows 110a, 110b, and 110c

FIG. 18 provides a second perspective view of high performance series fan tray 200, showing further details of high performance series fan module 106a (reference FIG. 17), which contains primary fan 8, diffuser element 14, and secondary fan 16, and operates as previously described. High performance series fan module 106a further contains primary fan indicator light 122a and secondary fan indicator light 124a.

It may be seen from FIG. 18 that control module 120 may contain Cubic Feet per Minute (CFM) or temperature display 126, increase increment button 130, decrease increment

button 128, and power switch 132. The CFM, temperature, or other set point may be increased or decreased by pressing increase increment button 130 or decrease increment button 128, respectively, causing control module 120 to adjust the power applied to high performance series fan modules 106a, 106b, and 106c (reference FIG. 17) accordingly. CFM or temperature display 126 may then be used to monitor the changing parameter as it moves towards, and then reaches, the new set point.

FIG. 19 illustrates high performance series fan tray 200 with primary fan 8c being replaced. Primary fan 8c may be removed while the thermal load within the cabinet or system being cooled remains active since control module 120 will increase the power applied to secondary fan 16c, and high performance series fan modules 106a and 106b (reference FIG. 17), during the primary fan 8c outage, and until primary fan 8c has been replaced, in order to maintain a relatively constant combined outlet airflow, comprised of output airflows 110a, 110b, and 110c (reference FIG. 17). Control module 120 may also be configured to detect the re-insertion of a new primary fan 8c, and then re-apply power to high performance series fan modules 106a, 106b, and 106c in a balanced fashion in order to optimize the performance of high performance series fan tray 100, as previously described.

FIG. 20 illustrates high performance series fan tray 200 with secondary fan 16c being replaced. Secondary fan 16c may be removed while the thermal load within the cabinet or system being cooled remains active since control module 120 will increase the power applied to primary fan 8c, and high performance series fan modules 106a and 106b (reference FIG. 17), during the secondary fan 16c outage, and until secondary fan 16c has been replaced, in order to maintain a relatively constant combined outlet airflow, comprised of output airflows 110a, 110b, and 110c (reference FIG. 17). Control module 120 may also be configured to detect the re-insertion of a new secondary fan 16c, and then to re-apply power to high performance series fan modules 106a, 106b, and 106c in a balanced fashion in order to optimize the performance of high performance series fan tray 100, as previously described.

FIG. 21 illustrates control module 120 operating in fan failure mode. Control module 120 is in communication with, and controls the power delivered to, primary fan modules 8a, 8b, and 8c, and secondary fan modules 16a, 16b, and 16c (reference FIG. 18,19,20),

and their respective indicator lights. Control module 120 may be configured to sense that secondary fan module 16b has failed, and to illuminate secondary fan module indicator light 124b accordingly. Controller module 120 may then adjust the power applied to cooling fan modules 106a, 106b, and 106c such that adjusted inlet airflows 138a and 138c are greater than normal inlet airflow 108 (shown here for reference only), and adjusted inlet airflow 138b, solely generated by primary fan module 114b, is as close to normal inlet air 108 as possible. Inlet flows 138a, 138b, and 138c may be adjusted in this manner such that the combined outlet airflow will be substantially equal to the sum of combined normal outlet airflows 110a, 110b, and 110c, and the thermal load within the system or cabinet being cooled will experience the same degree of forced convection cooling as with normal operation. Control module 120 may be configured to compensate for multiple fan module failures in a similar manner, however at some point the remaining fans may not be able to generate the full replacement airflow during the outage situation. Further, control module 120 may be configured to re-adjust power delivered to the cooling fan modules to normal levels once the defective fan(s) have been replaced, and turn off the indicator lights accordingly.

FIG. 22 illustrates a method for monitoring the airflow through high performance series fan module 106 using first pressure sensor 142 and second pressure sensor 144. Control module 120 may be in communication with both sensors, and may be configured to monitor the output from both sensors to determine the differential pressure between first pressure sensor 142 and second pressure sensor 144, as caused by the flow of air through diffuser element 14. Control module 120 may then use the differential pressure information to determine the rate of flow of air through diffuser element 14, and may further use the flow rate information as a feedback signal for an internal flow rate control algorithm. The power applied to primary fan 8 and secondary fan module 16 may be adjusted by control module 120 to compensate for any detected difference between the measured flow rate and the flow set point for high performance series fan module 106. A power adjustment that does not generate the predicted response, or does not generate a response that falls within normal guidelines, may indicate to the controller that primary fan 8 or secondary fan 16 is failing or has failed. Control module 120 may complete further tests, in like manner, to determine which fan has a problem, to determine the extent of that problem, and to determine an appropriate response.

FIG. 22 also illustrates swirl gap 140 between primary fan 8 and diffuser element 14. The swirl component of the flow produced by primary fan 8 will decay at an initial rate, and then decay at an ever decreasing rate as the distance from primary fan 8 increases. Swirl gap 140 allows sufficient space for some decay of swirl prior to diffuser element 14. This increases the effectiveness of diffuser element 14 since the swirl component at the inlet side of diffuser element 14 will have been reduced by some amount, and the net swirl decay caused by swirl gap 140 combined with diffuser element 14 will be greater than that caused by a diffuser element 14 placed immediately downstream from primary fan 8. The location and physical characteristics of diffuser 14 may be configured such that the swirl and other flow parameters meet or exceed the design specifications for secondary fan 16 as the flow enters secondary fan 16.

A small gap may be introduced between diffuser element 14 and secondary fan module 118 to reduce the acoustical noise produced high performance series fan module 106, and to allows sufficient space for second pressure sensor 144. This gap may be eliminated if second pressure sensor 144 is placed within diffuser element 14 116, at some distance from first pressure sensor 142, and if acoustic management is not an overriding design consideration.

Although diffuser element 14 has a very positive effect on the efficiency and performance of high performance series fan module 106, as previously described, it does introduce a small flow restriction and a corresponding pressure drop. Although this is acceptable during normal operation, it does limit the maximum achievable flow rate when only one of primary fan 8 or secondary fan module 16 is operational. Therefore in some applications diffuser element 14 may be configured to slide out of the way, swing out of the way, or otherwise be partially or completely removed from the flow in order to maximize the achievable flow rate during an outage situation.

Accordingly, diffuser element 14 may be configured to be removable from the flow by splitting it in the middle, and allowing each half to swing towards primary fan module 8. The right half of diffuser element 14 and the left half of diffuser element 14 may be configured to swing along the right and left sides of high performance series fan module 106, respectively, and lie along the sides of the airflow channel in the area normally defined as swirl gap 140 during a fan outage situation. The sides of swirl gap 140 may

be configured to accommodate the right and left sides of diffuser element, so positioned, such that they present a minimum restriction to the flow. Control module 120 may be configured to release the right and left sides of diffuser element 14 during a fan outage, such that they must be manually returned to normal position when the defective fan has been replaced, and held there with a retaining mechanism controlled by control module 120, or to move the right and left sides of diffuser element 14 in a controlled fashion both during the outage and after it has been resolved.

FIG. 23 provides a perspective view of an alternatively configured high performance series fan tray with high performance series fan modules 106a and 106b mounted obliquely to provide a relatively even airflow over the maximum width possible with only two high performance cooling fan modules. Further, the primary and secondary cooling fans located within high performance series fan modules 106a and 106b, so mounted, may be conveniently removed by sliding them in the direction defined by removal arrows 156 and 154, respectively. Multiple high performance series fan modules may be configured obliquely, in this manner, and at various angles, to provide a relatively even airflow over a maximum possible width with the fewest possible number of high performance series fan modules. Further, this configuration offers fault tolerance with the fewest possible number of high performance series fan modules.

The present invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. Certain adaptations and modifications of the invention will be obvious to those skilled in the art. Therefore, the above-discussed embodiments are considered to be illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.